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Drying of a tape-cast layer: Numerical investigation of influencing parameters

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In this study, the evaporation of water from a ceramic-water mixture is investigated numerically with the purpose of understanding the drying process of the thin sheets produced by the tape casting process. In the scope of this work, a Representative Elementary Volume (REV) scale model concept for coupling non-isothermal multi-phase compositional porous-media flow and single-phase compositional laminar free-flow developed by Jabbari et al. (2016), is used for a thorough analysis of the influential parameters. Specifically, we investigate the influence of ventilation speed magnitude, v_{max}, the equivalent diameter of particles of the porous medium, d_p, the porosity of the porous medium, ϕ, the initial temperature in the free-flow region, T^{ff}, and the initial temperature in the porous-medium region, T^{pm}, on the characteristic drying curves of a thin ceramic layer. We, moreover, conduct a statistical analysis based on numerical experiments in combination with a fractional factorial design of the aforementioned parameters. The analysis accounts for the effects of parameters on the characteristic drying curves of a thin ceramic layer. The effects of varying each of the parameters as well as their mutual interaction are shown with particular attention to the maximal drying rate as well as the final time for the drying process.

1. Introduction

The use of tape casting (see Fig. 1) as a forming method for ceramics has increased over the last 50 years [1–3]. The process consists of three major sub-processes which are: (1) tape casting of an aqueous (fluid) ceramic slurry in a doctor blade configuration, (2) drying of the green tape, and (3) additional processing (which is often a sintering process). The first and third stages have been modelled extensively with numerical methods [4–8] whereas the second has remained almost unexplored numerically. An example of a simple numerical simulation for the evaporation of water based ceramics was first developed by [9], using a semi-coupled heat and mass transfer model.

A tape layer can be considered as a porous medium which contains powders and liquid phases [10], and evaporation takes place by one-sided heat and mass transport. After the slip (ceramic slurry) is spread into a thin layer, all of the solvent is removed from a single side of the tape. The two major mechanisms controlling the drying in the tape-cast layer are: (1) the rate of solvent (water in this study) evaporation from the surface of the cast and (2) the rate of solvent diffusion through the tape to the drying front.

The two aforementioned mechanisms can be changed by various means. The volatility of the solvent at the tape surface can be altered by adapting the types of solvent used, the concentration of solvent vapour in the local atmosphere, the local air temperature, and the solvent temperature. The diffusion rate through the tape layer can be varied by changing the binder concentration, altering particle size, adjusting the wet film temperature, and keeping an open pathway to the surface. Some of these control techniques, such as particle size and binder content, need to be addressed during the preparation of the slip and factored into the initial slip recipe. Other parameters like air temperature, slip temperature, and local vapour concentration are controlled by the drying equipment separate from the casting slip.

The evaporation process is normally characterized by the drying rate curve, and depending on the water content, it typically has three different stages [10–13]: (1) first a relatively constant and high evaporation rate, (2) a falling evaporation rate, and (3) a constant and low evaporation rate. These three stages influence the final property of the ceramic layer, in the sense that they can cause severe drying stresses as well as elongated drying time [10–14].

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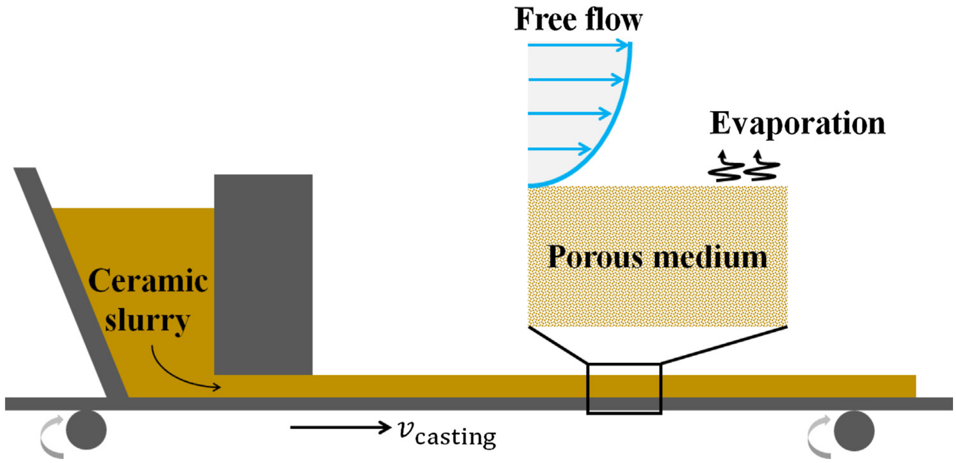

Fig. 1. 2D illustration of the tape casting process.

Consequently, crack initiation/growth might happen in the ceramic layer and cause a failure in the final product. Addressing the crack formation, high drying rates and elongated drying times are the main manufacturing issues, which should be avoided in tape casting of water based ceramic layers [10,15]. Hence, in this study the highest drying rate ($\dot{R}_{max}$) and the final time for drying (t_f) are chosen as design points with respect to maintaining crack free tapes during manufacturing.

Factorial design is a standard technique that establishes the importance of several variables in a pre-set range and the interaction between them [12,16,17]. Using this statistical tool, more information is obtained with less work; in fact, it is much more efficient in time and cost than the classical methods of experimental designs [18]. Furthermore, it can be used for optimization of linear and non-linear systems [19].

The aim of this paper is to simulate the evaporation phenomenon in the drying of a thin ceramic layer like in e.g. tape casting based on the models developed by [20]. The model is used to investigate the influence of important parameters in the drying process, i.e. ventilation speed magnitude, v_{max}, the equivalent diameter of particles of the porous medium, d_p, the porosity of the porous medium, ϕ, the initial temperature in the free-flow region, T^{ff}, and the initial temperature in the porous-media region, T^{pm}, on the characteristic drying curves. Furthermore, the model is used to conduct numerical experiments on the influence of different parameters affecting the drying behaviour, and a 2^{5-1} fractional factorial design based on the numerical simulations is applied to analyse the single and combined effects on the characteristic drying curves of a thin ceramic layer.

2. Model concept

The model concept is similar to the one used in [20]. The problem setting is illustrated in Fig. 2, in which two domains Ω^{ff} and Ω^{pm} are separated by the interface $\Gamma = \partial\Omega^{\text{ff}} \cap \partial\Omega^{\text{pm}}$ with the outward unit normal vectors $\mathbf{n}^{\text{ff}}$ and $\mathbf{n}^{\text{pm}}$. In the porous medium, Ω^{pm}, the multi-phase Darcy law in combination with a mass balance equation for the specific component under consideration as well as the total mass balance and an energy balance are used. Moreover, we assume local thermodynamic equilibrium to hold and all fluids to be Newtonian.

To simplify the system in the free-flow region, Ω^{ff}, we assume slow flow conditions, neglect the nonlinear inertia forces, and consider unsteady Stokes flow. Neglecting the inertia term is a simplification that is done in order to explain the coupling concept on the basis of a comparatively simple model. Coupling of the two domains is achieved using the two-domain approach.

The interface is assumed to be simple in the sense that it cannot store mass, momentum or energy, and assumes continuity of fluxes and local thermodynamic equilibrium [21]. Furthermore, the Beavers–Joseph–Saffman condition is employed in recognition of its theoretical limitation to single-phase, parallel flow [22,23].

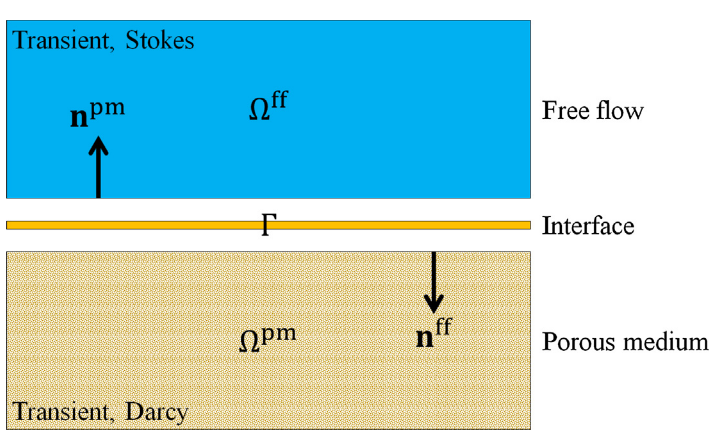

Fig. 2. Model set-up with a single phase in the free flow that interacts with two fluid phases in the porous medium.